



## SYNTHETIC BIOLOGY APPROACHES FOR ENVIRONMENTAL REMEDIATION OF DRUG RESIDUES

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### ABSTRACT

The increasing prevalence of pharmaceutical residues in the environment has emerged as a significant global concern due to their persistence, bioaccumulation, and potential to disrupt ecosystems and human health. Conventional wastewater treatment processes are often inadequate for the complete removal of these contaminants, necessitating the development of innovative and sustainable remediation strategies. Synthetic biology, an interdisciplinary field integrating molecular biology, genetic engineering, systems biology, and computational modeling, offers transformative solutions for the efficient degradation and removal of drug residues from environmental matrices. Engineered microorganisms, designed with tailored metabolic pathways, have demonstrated enhanced capabilities in degrading a wide range of pharmaceutical compounds, including antibiotics, hormones, analgesics, and antineoplastic agents. Techniques such as CRISPR-Cas gene editing, metabolic pathway optimization, and biosensor integration enable precise control over microbial functions and pollutant detection. Additionally, synthetic consortia and cell-free systems have been explored to improve biodegradation efficiency and minimize ecological risks associated with genetically modified organisms. Advances in biocontainment strategies, including kill switches and auxotrophy, further ensure environmental safety and regulatory compliance. This review highlights recent progress in synthetic biology-based approaches for environmental remediation of drug residues, focusing on microbial engineering,

enzymatic degradation, and integrated biotechnological systems. It also discusses challenges related to scalability, ecological impact, ethical considerations, and regulatory frameworks. Overall, synthetic biology presents a promising and sustainable avenue for mitigating pharmaceutical pollution, contributing to environmental protection and public health.

**Keywords:** Synthetic biology; Pharmaceutical residues; Environmental remediation; Biodegradation.

### INTRODUCTION

Pharmaceutical residues have become emerging environmental contaminants of significant concern due to their continuous release into ecosystems through anthropogenic activities such as drug manufacturing, improper disposal, agricultural runoff, and excretion following human and veterinary use. These residues, including antibiotics, nonsteroidal anti-inflammatory drugs, hormones, antidepressants, and anticancer agents, are frequently detected in surface water, groundwater, soil, and even drinking water supplies at trace concentrations. Despite their low levels, their persistent nature and biologically active properties can lead to adverse ecological effects, including endocrine disruption, development of antimicrobial resistance, and toxicity to aquatic and terrestrial organisms. Conventional wastewater treatment plants are not specifically designed to eliminate such micro pollutants, resulting in incomplete removal and continuous environmental exposure. In this context, the need for innovative, efficient, and sustainable



remediation strategies has become increasingly urgent[1]. Synthetic biology, a rapidly evolving field that combines principles of molecular biology, genetic engineering, computational modeling, and systems biology, offers novel solutions for addressing complex environmental challenges. By designing and constructing new biological systems or reprogramming existing organisms, synthetic biology enables the development of engineered microbes capable of selectively degrading pharmaceutical contaminants with high efficiency and specificity. Advances in gene editing technologies, particularly CRISPR-CA's systems, have revolutionized the ability to manipulate microbial genomes, facilitating the introduction of customized metabolic pathways for the breakdown of complex drug molecules. Additionally, synthetic gene circuits and regulatory networks allow for precise control of gene expression in response to environmental signals, enhancing the adaptability and performance of engineered organisms in diverse conditions. The integration of biosensors within these systems further enables real-time detection and monitoring of pharmaceutical pollutants, thereby improving process optimization and environmental surveillance [2]. Beyond single-species engineering, the construction of synthetic microbial consortia has emerged as a promising approach to mimic natural ecosystems and achieve synergistic degradation of multiple contaminants. Furthermore, cell-free synthetic biology platforms are being explored as safer alternatives, eliminating the risks associated with the release of genetically modified organisms into the environment. Despite these advancements, several challenges remain, including issues related to scalability, ecological safety, regulatory approval, and public acceptance. Addressing these concerns requires interdisciplinary collaboration and the development of robust biocontainment strategies such as kill switches and metabolic dependencies. [3].

### Pharmaceutical Pollution and Environmental Concerns

Pharmaceutical pollution has emerged as a critical environmental issue due to the continuous introduction of biologically active compounds into

ecosystems from human and veterinary medicine. These contaminants include antibiotics, analgesics, hormones, antidepressants, and anticancer drugs, which enter environmental compartments such as water bodies, soil, and sediments through various anthropogenic activities. Unlike conventional pollutants, pharmaceutical compounds are designed to exert specific biological effects at low concentrations, making even trace levels environmentally significant. Their persistent and pseudo-persistent nature results from continuous discharge and limited degradation, posing risks to aquatic organisms, terrestrial life, and ultimately human health. One of the major concerns associated with pharmaceutical pollution is the development of antimicrobial resistance (AMR), driven by the presence of sub-therapeutic concentrations of antibiotics in aquatic environments[4]. Additionally, endocrine-disrupting compounds, such as synthetic hormones, can interfere with the hormonal systems of wildlife, leading to reproductive abnormalities and population declines. Conventional wastewater treatment plants are not specifically engineered to remove these micro pollutants, leading to their widespread dissemination. Furthermore, bioaccumulation and biomagnification processes may increase the concentration of these compounds along the food chain, amplifying their toxicological effects. The environmental persistence of pharmaceuticals also raises concerns regarding chronic exposure and long-term ecological consequences, which are not fully understood. Increasing urbanization, industrialization, and pharmaceutical consumption have further exacerbated this issue globally. Regulatory frameworks are still evolving, and monitoring systems remain insufficient in many regions, particularly in developing countries[5]. Addressing pharmaceutical pollution requires an integrated approach involving advanced treatment technologies, sustainable drug design, proper disposal practices, and public awareness. Emerging solutions, such as green pharmacy and synthetic biology, hold promise for reducing environmental burdens. Overall, pharmaceutical pollution represents a complex and multifaceted challenge that necessitates interdisciplinary strategies to safeguard environmental and public health.

**Table 1: Types of Pharmaceutical Pollutants and Their Sources**

Pharmaceutical Pollutant	Source of Contamination
Antibiotics	Human and veterinary use, agricultural runoff
Analgesics	Human use, pharmaceutical manufacturing
Hormones	Agricultural runoff, human and veterinary use
Antidepressants	Human use, wastewater discharge
Anticancer Agents	Hospitals, pharmaceutical manufacturing

### Sources and Pathways of Drug Residues in the Environment

Drug residues enter the environment through a variety of sources and pathways, reflecting the extensive use of pharmaceuticals in human healthcare, veterinary practices, agriculture, and industrial processes. One of the

primary sources is the excretion of metabolized drugs and their metabolites from humans and animals, which are subsequently discharged into municipal wastewater systems. Hospitals and pharmaceutical manufacturing industries also contribute significantly to environmental contamination through effluents containing high

concentrations of active pharmaceutical ingredients. Improper disposal of unused or expired medications, such as flushing them down toilets or discarding them in landfills, further exacerbates the problem. In agricultural settings, the use of veterinary drugs and growth promoters in livestock leads to the contamination of soil and water through manure application and runoff. Aquaculture practices also introduce antibiotics and other drugs directly into aquatic environments[6]. Wastewater treatment plants, although designed to remove conventional pollutants, are often inefficient in eliminating pharmaceutical compounds, allowing them to pass through and enter surface water bodies such as rivers, lakes, and oceans. Additionally, sludge generated during wastewater treatment, which may contain accumulated drug residues, is often used as fertilizer, leading to soil contamination. Leaching and infiltration processes can further transport these compounds into groundwater systems, posing risks to drinking water sources. Atmospheric pathways, although less studied, may also contribute through the volatilization and deposition of certain pharmaceutical compounds. The complexity of these pathways results in widespread environmental distribution, making it difficult to control and manage pharmaceutical pollution effectively. Seasonal variations, population density, and healthcare practices also influence the concentration and distribution of drug residues in the environment. Understanding these sources and pathways is essential for developing targeted mitigation strategies and improving environmental management practices. Integrated approaches involving improved waste management, stricter regulations, and advanced treatment technologies are necessary to reduce the environmental burden of pharmaceutical contaminants[7].

### **Environmental Fate and Persistence of Pharmaceutical Compounds**

The environmental fate and persistence of pharmaceutical compounds are governed by their physicochemical properties, environmental conditions, and interactions with biotic and abiotic components of ecosystems. Once released into the environment, pharmaceuticals undergo various transformation processes, including biodegradation, photo degradation, hydrolysis, and sorption. However, many pharmaceutical compounds are structurally complex and designed to resist metabolic breakdown, contributing to their persistence in environmental matrices such as water, soil, and sediments. Factors such as pH, temperature, sunlight exposure, and microbial activity significantly influence the degradation rates of these compounds. Hydrophobic pharmaceuticals tend to adsorb onto soil particles and sediments, while hydrophilic compounds remain dissolved in water, facilitating their transport across aquatic systems. Some compounds may undergo partial degradation, resulting in the formation of transformation products that can be equally or more toxic than the parent compounds[8]. The persistence of pharmaceuticals leads

to their classification as pseudo-persistent pollutants due to their continuous input into the environment. Bioaccumulation in aquatic organisms and bio magnification along the food chain further amplify their ecological impact. For instance, certain antibiotics and endocrine-disrupting compounds have been shown to accumulate in fish and other aquatic organisms, affecting their physiological and reproductive functions. Groundwater contamination is particularly concerning, as it serves as a major source of drinking water in many regions. The long-term presence of pharmaceutical residues in the environment raises concerns about chronic exposure and subtle biological effects that may not be immediately evident. Additionally, interactions between different pharmaceutical compounds can lead to synergistic or antagonistic effects, complicating risk assessment. Advanced analytical techniques have improved the detection and quantification of these contaminants, but challenges remain in understanding their long-term environmental behavior. Addressing the persistence of pharmaceuticals requires the development of more biodegradable drug formulations, improved waste management practices, and advanced treatment technologies capable of effectively removing these contaminants from environmental systems[9].

### **Genetic Engineering Techniques in Environmental Applications**

Genetic engineering techniques have revolutionized environmental applications by enabling the design and development of microorganisms with enhanced capabilities for the degradation and removal of pharmaceutical pollutants. These techniques involve the manipulation of genetic material to introduce, modify, or regulate specific genes responsible for metabolic pathways associated with pollutant degradation. One of the most significant advancements in this field is the development of CRISPR-CA's systems, which allow precise and efficient genome editing, facilitating the insertion of genes encoding enzymes capable of breaking down complex pharmaceutical compounds. Recombinant DNA technology has been widely used to engineer bacteria and fungi with improved biodegradation efficiency, enabling them to metabolize a wide range of drug residues, including antibiotics, hormones, and analgesics. Metabolic pathway engineering further enhances these capabilities by optimizing enzymatic reactions and reducing metabolic bottlenecks, thereby increasing degradation rates[10]. Synthetic gene circuits and regulatory networks can be designed to control gene expression in response to environmental signals, ensuring that engineered organisms function efficiently under varying conditions. Additionally, the integration of omics technologies, such as genomics, proteomics, and metabolomics, provides insights into microbial pathways and facilitates the identification of target genes for engineering. Horizontal gene transfers and plasmid-based systems are also employed to introduce desirable traits into host organisms. Beyond single-species engineering,

synthetic microbial consortia are being developed to mimic natural ecosystems, allowing for the cooperative degradation of complex mixtures of pharmaceutical contaminants. These engineered systems can be deployed in bioreactors, wastewater treatment plants, or contaminated sites to enhance remediation efficiency. However, challenges such as genetic stability, ecological

impact, and regulatory concerns must be addressed to ensure safe and effective application. Overall, genetic engineering techniques offer powerful tools for developing innovative and sustainable solutions to environmental pollution caused by pharmaceutical residues [11].

**Table 2: Engineered Microorganisms for Pharmaceutical Degradation**

Microorganism/Strain	Pollutants Degraded	Genetic Engineering Techniques Used	Efficiency
<i>Escherichia coli</i>	Antibiotics, hormones	CRISPR-CA's, Metabolic pathway optimization	High
<i>Pseudomonas putida</i>	Analgesics, antibiotics	Recombinant DNA, metabolic pathway engineering	Moderate
<i>Saccharomyces cerevisiae</i>	Anticancer agents	Synthetic gene circuits	High

### Biosensors for Detection and Monitoring of Drug Residues

Biosensors have emerged as powerful analytical tools for the detection and monitoring of pharmaceutical residues in environmental matrices, offering high sensitivity, specificity, and rapid response compared to conventional analytical methods. These devices integrate a biological recognition element, such as enzymes, antibodies, nucleic acids, or whole cells, with a transducer that converts the biological interaction into a measurable signal. Biosensors can detect a wide range of pharmaceutical compounds, including antibiotics, hormones, and analgesics, even at trace concentrations. Advances in nanotechnology and synthetic biology have significantly enhanced the performance of biosensors, enabling the development of highly sensitive and portable devices suitable for real-time environmental monitoring. Genetically engineered microorganisms can be designed as whole-cell biosensors that produce detectable signals, such as fluorescence or luminescence, in response to specific drug residues. Additionally, aptameric-based and immunosensors offer high selectivity for target molecules, making them valuable for environmental analysis[12]. Electrochemical, optical, and piezoelectric transducers are commonly used to convert biological interactions into quantifiable signals. Integration with microfluidic systems and wireless technologies has further enabled the development of smart bio sensing platforms capable of continuous monitoring and data transmission. These advancements facilitate early detection of pharmaceutical pollution, allowing for timely intervention and mitigation. Biosensors also play a crucial role in assessing the efficiency of remediation processes by monitoring changes in pollutant concentrations. Despite their advantages, challenges such as stability, reproducibility, and interference from complex environmental matrices need to be addressed for widespread application. Standardization and validation of biosensor technologies are essential for their integration into regulatory frameworks. Overall, biosensors represent a promising approach for enhancing environmental surveillance and management of pharmaceutical contaminants,

contributing to improved ecosystem health and public safety[13].

### Environmental and Safety Considerations

The application of advanced biotechnological approaches, particularly synthetic biology and genetically engineered systems, for environmental remediation of pharmaceutical residues necessitates careful consideration of environmental and safety aspects. While these technologies offer significant advantages in terms of efficiency and specificity, their potential ecological impacts must be thoroughly evaluated. One of the primary concerns is the unintended release of genetically modified organisms into natural ecosystems, which may disrupt existing microbial communities and ecological balance. Horizontal gene transfer between engineered and native microorganisms could lead to the spread of modified genetic traits, with unpredictable consequences. Additionally, the metabolic byproducts generated during the degradation of pharmaceutical compounds may exhibit toxicity or persistence, posing further environmental risks. The stability and survivability of engineered organisms under environmental conditions also influence their effectiveness and safety[14]. Risk assessment studies are essential to evaluate the potential impacts on non-target organisms, biodiversity, and ecosystem functions. Regulatory frameworks governing the use of genetically engineered organisms vary across regions and often require extensive safety evaluations before approval for environmental applications. Ethical considerations and public perception also play a crucial role in the acceptance of these technologies. Strategies such as controlled deployment in contained systems, including bioreactors and wastewater treatment plants, can minimize environmental exposure. Continuous monitoring and evaluation of engineered systems are necessary to ensure their safe operation. Advances in computational modeling and ecological risk assessment tools have improved the ability to predict and mitigate potential risks. Collaboration between scientists, policymakers, and stakeholders is essential to develop guidelines and standards for the safe application of these technologies. Overall, balancing the benefits of innovative

remediation approaches with environmental safety is critical for their sustainable implementation[15].

### Biocontainment Strategies and Biosafety Measures

Biocontainment strategies and biosafety measures are critical components in the application of synthetic biology for environmental remediation, particularly when utilizing genetically engineered microorganisms. These strategies are designed to prevent the unintended spread and persistence of engineered organisms in natural ecosystems, thereby minimizing ecological risks. One of the most widely used approaches is the incorporation of genetic “kill switches,” which are engineered regulatory systems that trigger cell death under specific environmental conditions, such as the absence of a particular nutrient or the presence of a specific signal. Auxotroph-based containment is another effective strategy, where engineered organisms are made dependent on externally supplied nutrients that are not available in the natural environment, ensuring that they cannot survive outside controlled settings. Additionally, gene circuit designs can be implemented to limit the replication and lifespan of engineered microbes, enhancing their safety profile[16]. Physical containment methods, such as the use of bioreactors and

immobilization techniques, further reduce the risk of environmental release. Advances in synthetic biology have also enabled the development of orthogonal biological systems that operate independently of natural cellular processes, minimizing the potential for horizontal gene transfer. Biosafety measures include rigorous risk assessment, monitoring, and adherence to regulatory guidelines governing the use of genetically modified organisms. Standard operating procedures and containment protocols must be established to ensure safe handling, storage, and disposal of engineered organisms. Public and environmental health considerations are central to biosafety frameworks, necessitating transparency and stakeholder engagement. Despite these advancements, challenges remain in ensuring the long-term stability and reliability of biocontainment systems under variable environmental conditions. Continuous research and innovation are required to develop more robust and fail-safe containment strategies[17]. Overall, effective biocontainment and biosafety measures are essential for the responsible deployment of synthetic biology technologies in environmental remediation, ensuring that their benefits are realized without compromising ecological integrity.

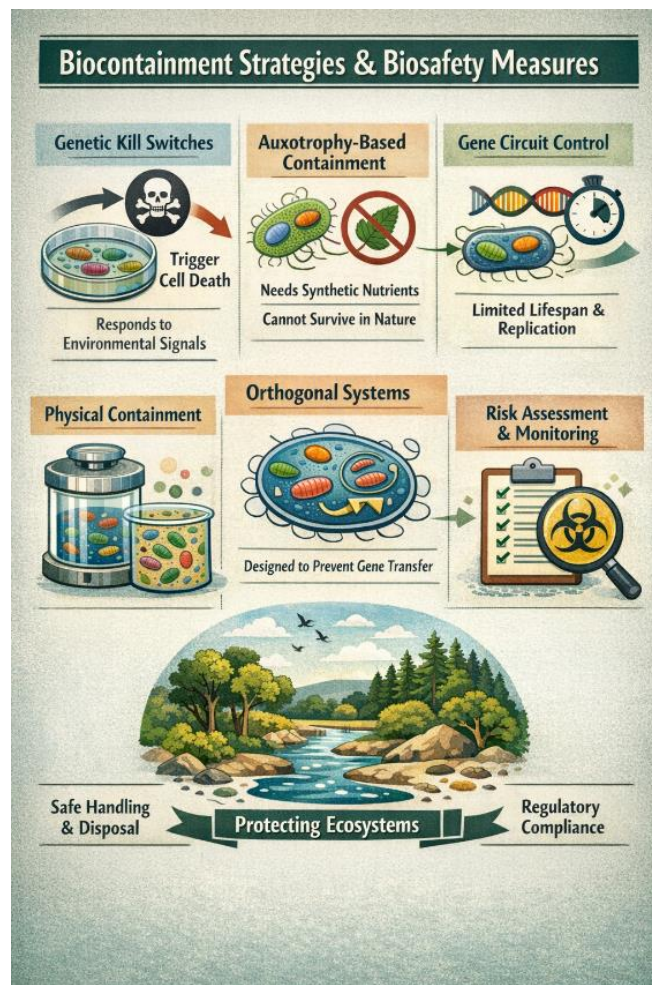


Figure 1: Biocontainment Strategies and Biosafety Measures

### **Risk Assessment and Environmental Monitoring**

Risk assessment and environmental monitoring are essential components in managing the impact of pharmaceutical residues and evaluating the safety of remediation technologies. Risk assessment involves the systematic evaluation of the potential adverse effects of pharmaceutical contaminants on human health and the environment, considering factors such as exposure levels, toxicity, and persistence. It typically includes hazard identification, dose-response assessment, exposure assessment, and risk characterization. Advanced modeling tools and predictive analytics are increasingly used to assess the environmental risks associated with pharmaceutical pollutants and engineered remediation systems. Environmental monitoring, on the other hand, involves the regular sampling and analysis of environmental matrices such as water, soil, and sediments to detect and quantify pharmaceutical residues. High-performance analytical techniques, including liquid chromatography-mass spectrometry (LC-MS), enable the detection of contaminants at trace levels. The integration of biosensors and remote sensing technologies has further enhanced real-time monitoring capabilities[18]. Monitoring data are crucial for evaluating the effectiveness of remediation strategies and ensuring compliance with regulatory standards. Additionally, long-term monitoring helps identify trends and emerging risks associated with pharmaceutical pollution. Eco toxicological studies are also conducted to assess the impact of contaminants on various organisms, providing insights into potential ecological effects. The complexity of environmental systems and the presence of multiple contaminants pose challenges in risk assessment and monitoring. Interdisciplinary approaches combining chemistry, biology, and environmental science are necessary to address these challenges effectively. Regulatory agencies play a key role in establishing guidelines and standards for risk assessment and monitoring. Public access to monitoring data and transparency in reporting are important for building trust and ensuring accountability. Overall, robust risk assessment and environmental monitoring frameworks are essential for protecting environmental and public health in the context of pharmaceutical pollution.

### **Ethical Considerations in Environmental Biotechnology**

Ethical considerations in environmental biotechnology, particularly in the application of synthetic biology for remediation purposes, are increasingly important as technological capabilities expand. The deliberate modification of organisms to degrade pharmaceutical pollutants raises questions regarding the moral responsibility of altering natural systems and the potential unintended consequences of such interventions. One of the primary ethical concerns is the release of genetically engineered organisms into the environment, which may have irreversible ecological impacts and affect

biodiversity. Issues related to biosafety, risk management, and long-term environmental consequences must be carefully addressed. Additionally, the concept of “playing God” by designing and manipulating life forms has sparked philosophical debates about the limits of human intervention in nature. Public perception and acceptance of these technologies are influenced by cultural, social, and ethical values, making stakeholder engagement and transparent communication essential. Equity and access are also important ethical considerations, as the benefits of environmental biotechnology should be distributed fairly across different regions and communities, particularly in developing countries that may be disproportionately affected by pollution[19]. Intellectual property rights and the commercialization of genetically engineered solutions raise concerns about accessibility and affordability. Ethical frameworks must also consider the potential misuse of synthetic biology technologies for harmful purposes. Regulatory oversight and governance play a crucial role in ensuring that research and applications are conducted responsibly and ethically. Education and awareness programs can help inform the public and promote informed decision-making. Interdisciplinary collaboration among scientists, ethicists, policymakers, and the public is essential to address these complex issues. Ultimately, ethical considerations must be integrated into the development and implementation of environmental biotechnology to ensure that technological advancements align with societal values and contribute to sustainable and responsible environmental management.

### **Degradation of Hormones and Endocrine Disruptors**

The degradation of hormones and endocrine-disrupting compounds (EDCs) is a critical aspect of environmental remediation due to their profound effects on biological systems even at extremely low concentrations. EDCs, including natural and synthetic hormones such as estrogen, progesterone, and ethinylestradiol, are widely used in pharmaceuticals and are frequently detected in aquatic environments as a result of human and veterinary activities. These compounds can interfere with the endocrine systems of organisms, leading to reproductive abnormalities, developmental defects, and altered behavior in wildlife. Conventional wastewater treatment processes are often ineffective in completely removing these compounds, necessitating the development of advanced remediation strategies. Synthetic biology offers innovative solutions by enabling the design of engineered microorganisms and enzymes capable of specifically targeting and degrading EDCs. Enzymes such as laccases, peroxidases, and cytochrome P450 monooxygenases have shown significant potential in the biotransformation of hormone compounds into less toxic metabolites. Genetic engineering techniques can enhance the expression and activity of these enzymes, improving degradation efficiency. Additionally, synthetic microbial consortia can be developed to achieve synergistic degradation of complex mixtures of EDCs. Advanced oxidation

processes and nanotechnology-based approaches can also be integrated with biological systems to enhance removal efficiency. Monitoring the degradation process is essential to ensure that intermediate products do not exhibit residual toxicity. Environmental factors such as pH, temperature, and microbial community dynamics influence the degradation rates of EDCs. Regulatory frameworks and guidelines are increasingly focusing on the control and monitoring of endocrine disruptors due to their significant ecological and health impacts. Continued research and innovation are required to develop efficient, sustainable, and safe methods for the degradation of these compounds. Overall, addressing the challenge of hormone and endocrine disruptor contamination is essential for protecting ecosystem integrity and public health.

## CONCLUSION

Synthetic biology has emerged as a transformative and highly promising approach for addressing the growing challenge of pharmaceutical pollution in the environment. The persistent presence of drug residues, including antibiotics, hormones, analgesics, and cytotoxic agents, poses significant risks to ecosystems and human health, necessitating innovative and sustainable remediation strategies beyond conventional treatment methods. In this context, synthetic biology offers unparalleled opportunities by enabling the rational design and engineering of biological systems with enhanced specificity, efficiency, and adaptability for the degradation of complex pharmaceutical compounds. Engineered microorganisms, optimized metabolic pathways, and advanced gene-editing tools such as CRISPR-Cas systems have collectively expanded the scope of bioremediation, allowing targeted breakdown of contaminants that are otherwise resistant to traditional processes. Furthermore, the development of synthetic microbial consortia and enzyme-based systems has demonstrated the potential for synergistic and accelerated degradation of diverse drug residues in complex environmental matrices. The integration of biosensors and real-time monitoring technologies further enhances the

effectiveness of these systems by enabling precise detection and control of remediation processes. Despite these advancements, the practical implementation of synthetic biology in environmental applications is accompanied by several challenges that must be carefully addressed. Issues related to ecological safety, genetic stability, potential horizontal gene transfer, and unintended environmental consequences require robust risk assessment and stringent regulatory oversight. The development of effective biocontainment strategies, including genetic kill switches and metabolic dependencies, is crucial to ensure the safe deployment of engineered organisms. Additionally, ethical considerations, public acceptance, and policy frameworks play a pivotal role in determining the feasibility and scalability of these technologies. From a translational perspective, the integration of synthetic biology with complementary approaches such as nanotechnology, artificial intelligence, and advanced oxidation processes holds significant promise for enhancing remediation efficiency and scalability. Future research should focus on improving the robustness and resilience of engineered systems under variable environmental conditions, as well as developing cost-effective and energy-efficient solutions suitable for large-scale applications. Interdisciplinary collaboration among scientists, engineers, policymakers, and stakeholders will be essential to bridge the gap between laboratory innovations and real-world implementation. Moreover, the adoption of green chemistry principles and sustainable drug design can complement remediation efforts by reducing the environmental burden at the source. In conclusion, synthetic biology represents a paradigm shift in environmental remediation strategies, offering innovative, precise, and sustainable solutions for mitigating pharmaceutical pollution. With continued advancements, responsible governance, and public engagement, it has the potential to significantly contribute to environmental protection, ecosystem sustainability, and global public health.

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